Chapter 1
Introduction

1.1 Overview

1.1.1 Purpose

Final cover systems (hereafter referred to as “cover systems”) are used at landfills and other types of waste management units (e.g., waste piles and surface impoundments) to contain waste and any waste by-products (e.g., leachate or landfill gas), control moisture and air infiltration into the waste, and prevent the occurrence of odors, disease vectors, and other nuisances. Cover systems are also used to meet erosion, aesthetic, and other post-closure site end use criteria for waste management sites. These systems are intended to achieve their functional requirements for time periods of many decades to hundreds of years.

As illustrated by Figure 1-1, cover systems form one component of the integrated group of engineered systems used at landfills to protect human health and the environment. Other components include liners, daily and intermediate covers, leachate collection and removal systems, gas collection and removal systems, and surface-water management systems.

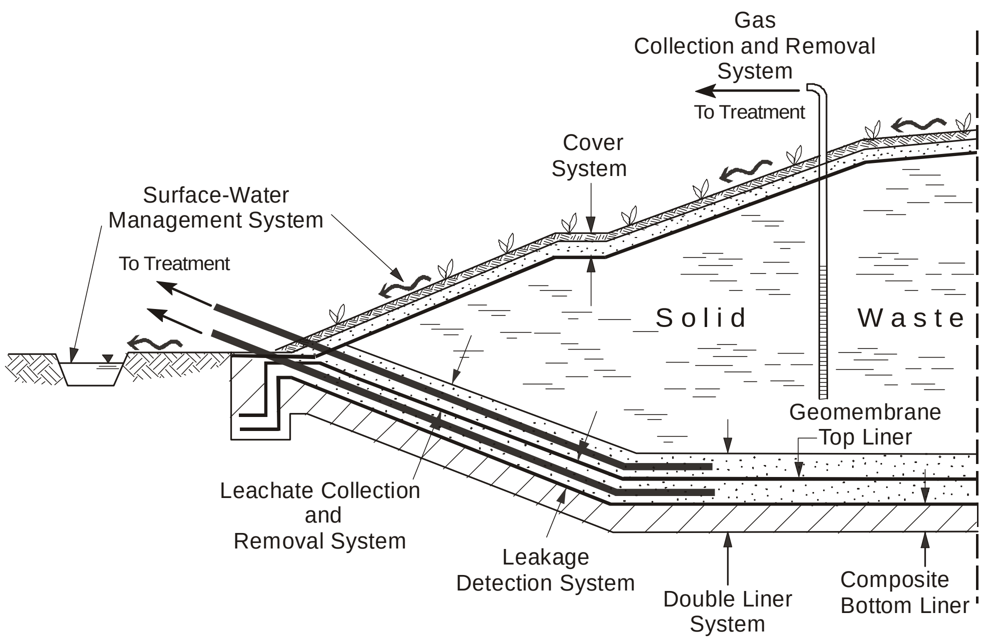


Figure 1-1. Example of Engineered Systems Used at Landfills.

Cover systems are also placed over old dumps as part of the remediation and final closure of these facilities and over contamination source areas that can be at the ground surface or at shallow depth. When used for these applications, the cover system may again be one component of an integrated group of engineered systems used for facility closure or source containment (Figure 1-2). The cover system components for these facilities are generally the same as, or similar to, the components used to close new landfills. However, as discussed subsequently in this document, some of the design issues faced in closing dumps or in implementing source containment remedies at contaminated sites are different from the design issues faced in closing new landfills.

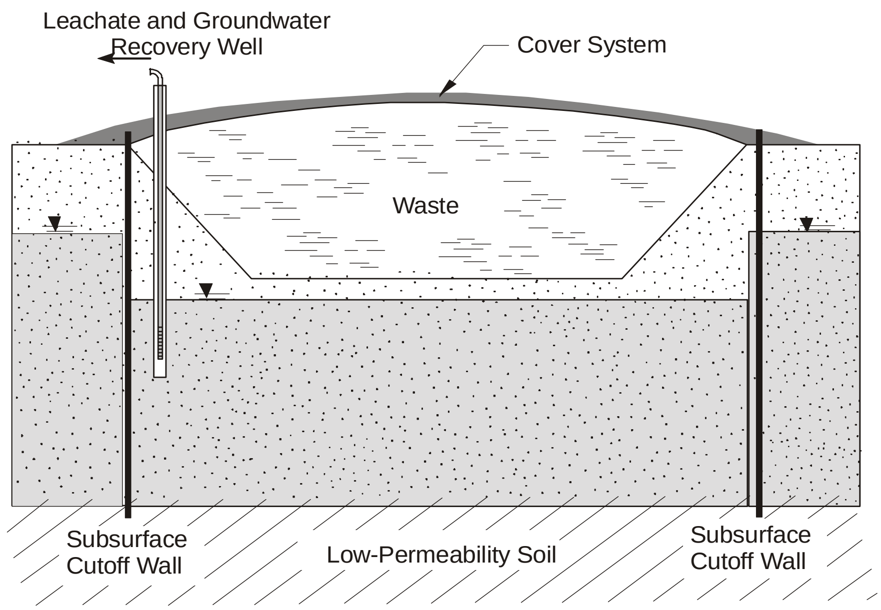


Figure 1-2. Example of Engineered Systems Used at Old Dumps or Contamination Source Areas.

The cover system itself can consist of multiple layers of different types of soils and/or geosynthetics, each with one or more specific functions. The cover system components are briefly introduced in Section 1.5 and discussed in more detail in Chapter 2. The waste to be contained can be municipal solid waste (MSW), hazardous waste (HW), low-level radioactive waste, industrial waste (IW), remediation waste, incinerator or coal-combustion ash, construction and demolition waste (C&DW), sewage treatment or industrial process sludge, or some other material. The cover system is installed on top of the waste shortly after a specific landfill cell or unit has been filled to capacity in the case of a new landfill, at the time of site remediation and closure in the case of an old dump, or at the time of site remediation in the case of a contaminated site.

The purpose of this guidance document is to provide information to facility owners/operators, engineers, and regulators regarding cover systems for MSW and HW landfills regulated under the Resource Conservation and Recovery Act (RCRA) and sites being remediated under the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA). This guidance document provides an update to the previous U.S. Environmental Protection Agency (EPA) guidance on this subject "*Design and Construction of RCRA/CERCLA Final Covers*" (EPA, 1991a). Although gas management issues are discussed in Section 1.4 and Chapter 5 of this document, the information provided on regulatory requirements for MSW landfills under the Clean Air Act (CAA) is cursory and is not the intended use of this guidance document.

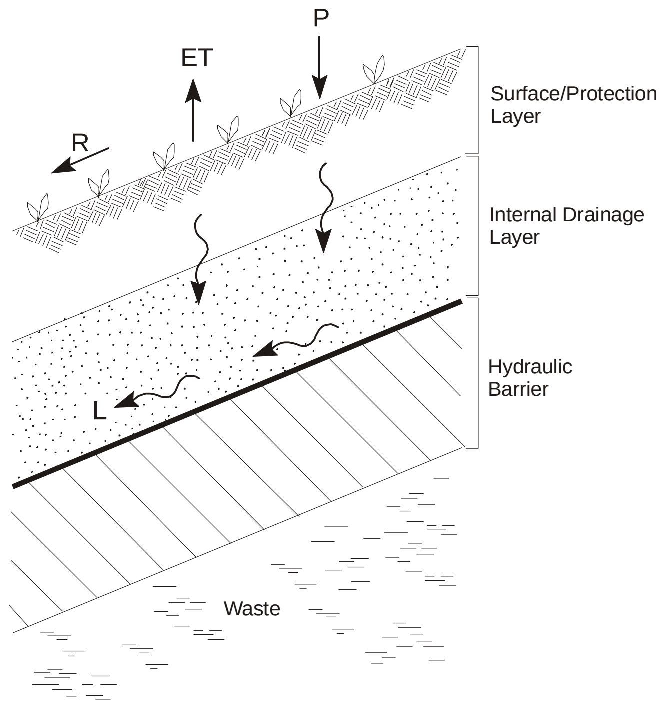
In comparison to the scope of the 1991 EPA cover system guidance document, the scope of this document has been expanded to address a number of new topics including design criteria development, new types of geosynthetics (such as geosynthetic clay liners (GCLs)), alternative materials and designs (including evapotranspiration (ET) barriers and capillary barriers), special design issues, lessons learned from the closure of existing landfills, performance monitoring of cover systems, maintenance of cover systems to achieve the required design life, and site end use. Significant advances in the technology for cover system design and construction have occurred since 1991. These advances are reflected in this document.

1.1.2 Classification of Cover Systems

At present, cover system designs are based on one or more of three different principles for preventing or minimizing water percolation into waste. Each of these is briefly discussed below.

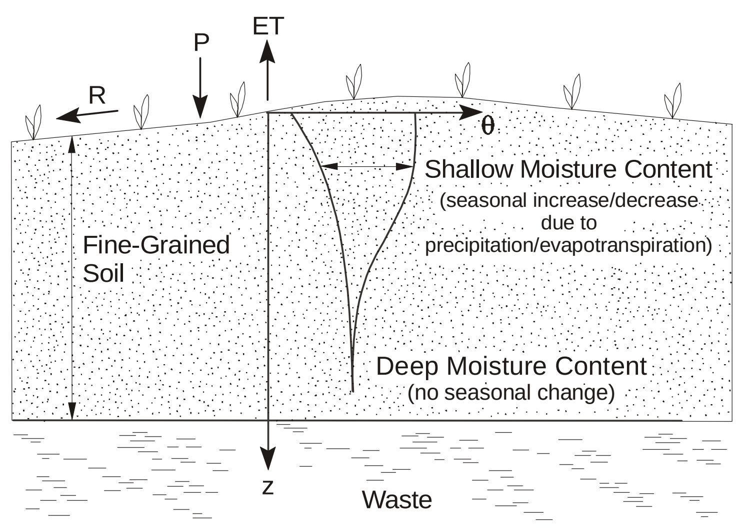
Hydraulic Barrier: This type of cover system uses a low-permeability physical barrier to impede the downward migration of water into the waste (Figure 1-3). Hydraulic barrier materials most commonly include compacted clay liners (CCLs), GCLs, geomembranes (GMs), and combinations of these materials. Other barrier materials (e.g. asphaltic concrete) have also been used. A hydraulic barrier is generally used with additional cover system components. However, recently, at a few MSW landfill sites, a GM barrier was used alone as a cover system (Gleason et al., 1998, 1999, 2001). In many cases and especially on sideslopes, an internal drainage layer is included above the hydraulic barrier to drain the overlying layers, promote lateral drainage, and prevent the buildup of hydraulic head in the cover system. A surface/protection layer is often installed as the topmost layer to protect the hydraulic barrier from erosion, exposure to wet-dry cycles, exposure to freeze-thaw cycles, biointrusion (intrusion by plant roots, burrowing animals, and humans), and ultraviolet degradation and for temporary storage of infiltrating water for subsequent uptake by vegetation, if present. Water movement through cover systems with hydraulic barriers can occur as either saturated or unsaturated flow, depending on site-specific conditions (particularly climate). Current EPA regulations and existing requirements for cover systems at landfills are developed around the use of hydraulic barriers.

ET Barrier: This type of cover system has been developed for use at arid and semi-arid sites. ET barriers consist of a thick layer of relatively fine-grained soil capable of supporting vegetation (Figure 1-4).



P = Precipitation
ET = Evapotranspiration
R = Runoff
L = Lateral Drainage

Figure 1-3. Hydraulic Barrier Type of Cover System.



P = Precipitation
ET = Evapotranspiration
R = Runoff
θ = Volumetric Moisture Content
z = Depth

Figure 1-4. ET Barrier Type of Cover System and Representative Soil Moisture Content vs. Depth Profile.

Soil types used for construction of ET barriers include silty sands, silts, and clayey silts. ET barriers exploit two characteristics of fine-grained soils: (i) high water storage capacity (i.e., they can store a significant amount of water before gravity drainage: they have a high field capacity); and (ii) low hydraulic conductivity, even at high degrees of saturation. High soil water storage capacity allows storage of water that infiltrates the barrier until it can later be removed by ET. Low hydraulic conductivity limits advancement of the wetting front into the barrier during seasonal wet periods (rainfall or snow melt). An ET barrier must be sufficiently thick such that the soil water content does not increase near the base of the barrier; all changes in soil water storage should occur in the upper portion of the barrier (Figure 1-4). Otherwise, percolation through the cover system can occur. The required barrier thickness is a function of the frequency and intensity of precipitation, the unsaturated hydraulic properties of the soil, the type and vigor of vegetative cover, the rate at which water can be removed by ET, and other factors. Barrier thickness typically ranges from about 0.9 m to more than 2 m. ET barriers often have a surface layer to support vegetation and provide erosion protection.

Capillary Barrier: This type of cover system has also been developed for use at arid and semi-arid sites. Capillary barriers consist of one or more layers of finer-grained soil overlying one or more layers of coarser-grained soil. The finer-grained soil layer of the capillary barrier has a higher water storage capacity than a comparable layer at the same depth without the capillary break (i.e., a free-draining layer such as an ET barrier). Figure 1-5 illustrates the simplest configuration for a capillary barrier: a single finer-grained (e.g., clayey silt) soil layer over a coarser-grained (e.g., sandy) soil layer. At low degrees of soil saturation (i.e., at low matric potential in Figure 1-5), the hydraulic conductivity of the coarser-grained soil is much less than that of the finer-grained soil. This is the reverse of the condition that occurs at high degrees of soil saturation. Capillary barriers store infiltrating water in the finer-grained soil until the water can be removed by subsequent ET. If they are sloped, capillary barriers can also divert infiltrating water via unsaturated lateral flow in the finer-grained soil (above the soil interface). Sometimes a “wicking layer” (with intermediate characteristics to the coarser- and finer-grained layers) is installed between the coarser- and finer-grained layers to convey lateral flow. At high degrees of soil saturation (e.g., in a humid climate), the capillary effect breaks down and percolation through the cover system can occur. Like ET barriers, capillary barriers often have a surface layer to support vegetation and provide erosion protection.

This guidance document focuses primarily on the hydraulic barrier type of cover system with limited commentary on the other two types provided mainly in Chapter 3. It is noted, however, that the use of ET and capillary barrier types of cover systems is becoming more common, particularly in arid and semi-arid regions of the U.S. While these alternative designs can be adequate for hydraulic control, they should generally not be used without gas containment components at MSW landfill sites where landfill gas collection control are needed to prevent offsite gas migration and reduce emissions that are of concern to human health and the environment.

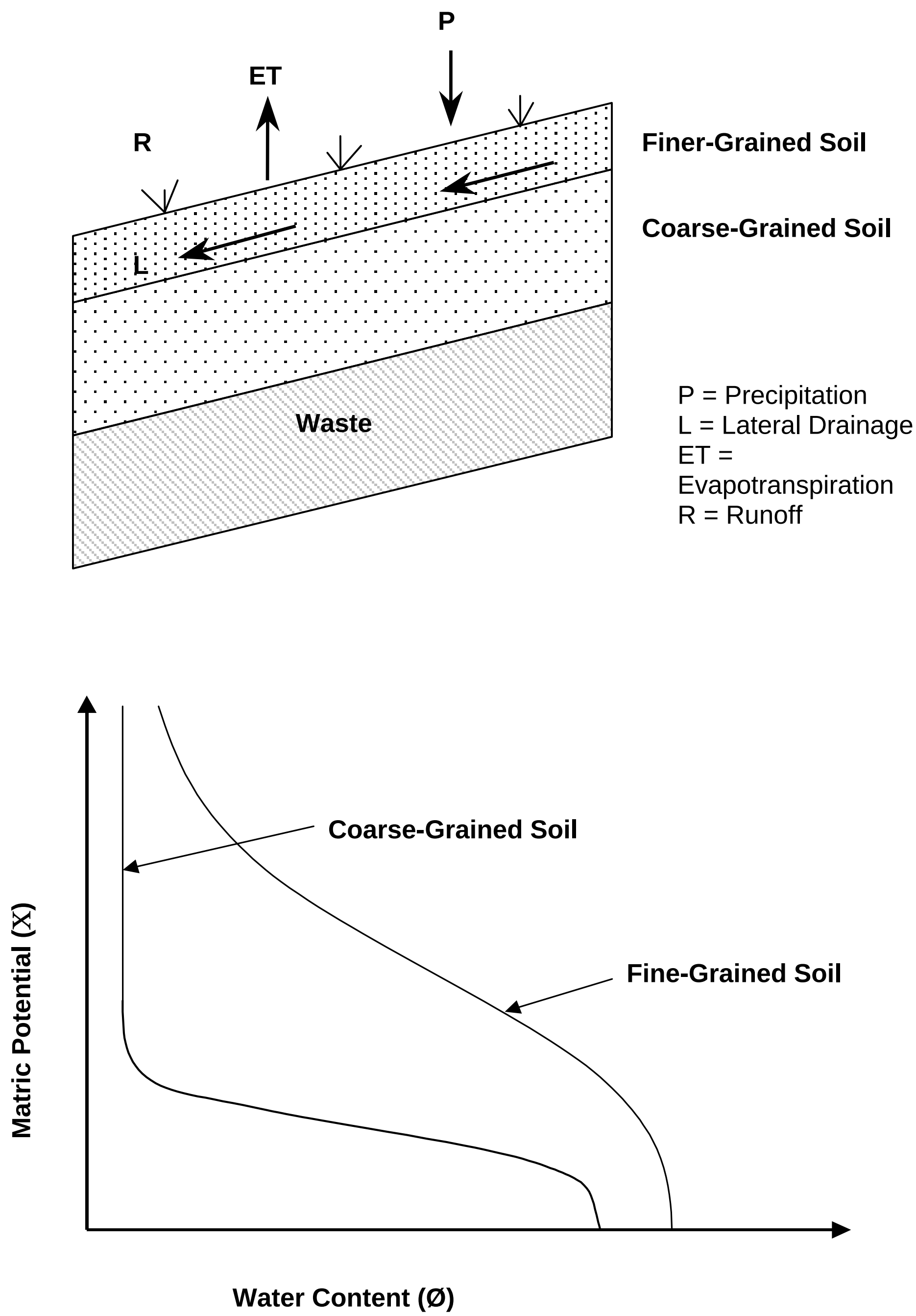


Figure 1-5. Capillary Barrier Type of Cover System and Representative Unsaturated Hydraulic Conductivity Functions.

1.1.3 Organization of Document

The remainder of this document is organized into the following chapters:

- individual components of cover systems (Chapter 2);
- alternative design concepts and materials (Chapter 3);
- hydraulic analysis and design (Chapter 4);
- gas emission analysis and collection system design (Chapter 5);
- geotechnical analysis and design (Chapter 6);
- lessons learned (Chapter 7);
- performance monitoring (Chapter 8); and
- maintenance and site end use (Chapter 9).

1.2 Closure Regulatory Requirements

A starting point in understanding closure requirements for landfills or source area containment for contaminated sites is to become familiar with the regulations governing the landfill or environmental remediation project. Federal regulations applicable to cover systems for RCRA and CERCLA projects are briefly reviewed in this section of the guidance document.

1.2.1 MSW Landfill Cover Systems

Minimum technical requirements for closure of MSW landfills (MSWLFs) regulated under RCRA Subtitle D are contained in Title 40 of the Code of Federal Regulations, Section 258.60 (40 CFR §258.60). The regulation allows either a prescriptive minimum criteria cover system or a performance-based cover system design. The specific requirements of that regulation are as follows:

> "*(a) Owners or operators of all MSWLF units must install a final cover system that is designed to minimize infiltration and erosion. The final cover system must be designed and constructed to:*
> *(1) Have a permeability less than or equal to the permeability of any bottom liner system or natural subsoils present, or a permeability no greater than 1 x 10^{-5} cm/sec, whichever is less, and*
> *(2) Minimize infiltration through the closed MSWLF by the use of an infiltration layer that contains a minimum 18-inches of earthen material, and*
> *(3) Minimize erosion of the final cover by the use of an erosion layer that contains a minimum 6-inches of earthen material that is capable of sustaining native plant growth.*
> *(b) The Director of an approved State may approve an alternative final cover design that includes:*
> *(1) An infiltration layer that achieves an equivalent reduction in infiltration as the infiltration layer specified in paragraphs (a)(1) and (a)(2) of this section, and*
> *(2) An erosion layer that provides equivalent protection from wind and water erosion as the erosion layer specified in paragraph (a)(3) of this section.*"

The foregoing regulations were developed largely based on consideration of non-technical factors such as cost and socio-economic impact, particularly for existing landfills. After the foregoing regulations were issued in October 1991, EPA clarified their intent with respect to the permeability requirement of the prescriptive minimum criteria cover system in 40 CFR §258.60(a)(1). The Agency's clarification was contained in the Federal Register in June 1992, at 57 FR 28628 (EPA, 1992b). According to this clarification, the cover system is required to have a hydraulic conductivity less than or equal to that of any underlying liner system or natural subsoils. The purpose of this requirement is to prevent what the Agency calls the "bathtub" effect, wherein percolation into the landfill exceeds leakage through the liner system, causing the accumulation of liquid in the facility. The hydraulic conductivity must also be no greater than 1×10^{-7} m/s.

The EPA (1992b) clarification to the minimum requirements for MSW landfill cover systems is illustrated in Figure 1-6 for: (i) unlined landfills constructed prior to the effective date of Subtitle D regulations (Figure 1-6(a)); (ii) landfills with a CCL beneath the waste (Figure 1-6(b)); and (iii) landfills underlain by a Subtitle D composite liner consisting of a GM upper component and a CCL lower component (with the CCL having a maximum hydraulic conductivity of 1×10^{-9} m/s) (Figure 1-6(c)). While these minimum requirements seem to indicate that less protective cover systems are allowed at landfills with less protective liner systems, EPA believes that, all other factors being equal (e.g., comparable hydrogeologic setting, types of waste, etc.), more protective cover systems should be used at unlined landfills compared to lined landfills to minimize the percolation of water though the cover systems and, consequently, the formation of leachate and migration of such leachate from the units.

It should also be noted that the cover systems required by 40 CFR §258.60 regulations do not represent "complete" designs in the sense that they are based on a permeability design criterion only and do not address other design criteria. For example, the cover system shown in Figure 1-6(c) does not include a drainage layer above the GM barrier or an adequate thickness of cover soil to allow sufficient water storage for healthy surface vegetation. As another example, none of the designs presented in Figure 1-6 have an adequate thickness of soil protection above the CCL component of the cover system to protect the CCL from freeze-thaw damage for sites located in northern climates. As a final example, none of the designs addresses the important matter of landfill gas transmission beneath the cover system.

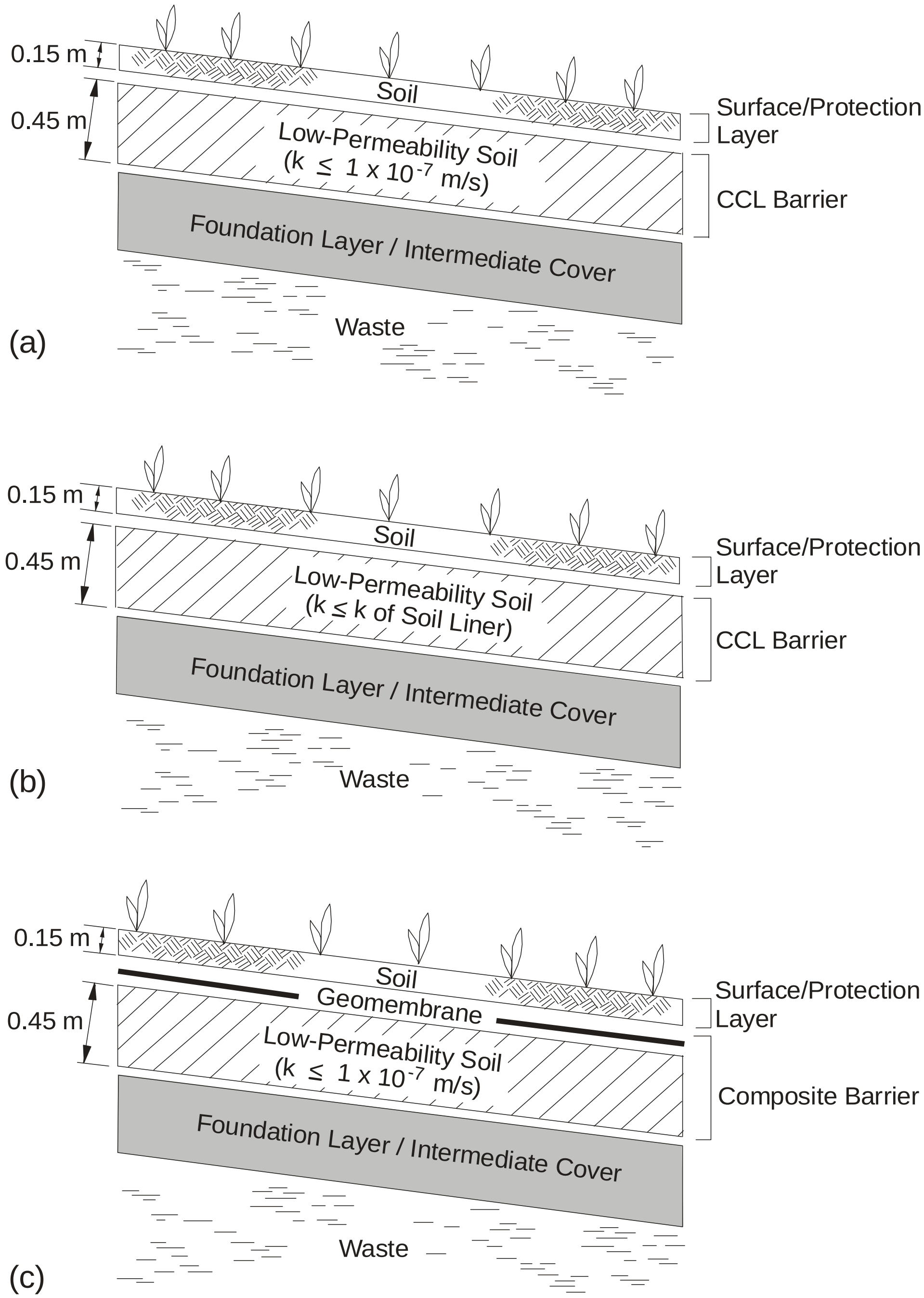


Figure 1-6. EPA Prescriptive Minimum Criteria Cover Systems for: (a) Unlined MSW Landfills; (b) MSW Landfills Underlain by a CCL; and (c) MSW Landfills Underlain by a GM/CCL Composite Liner.

1.2.2 Hazardous Waste Landfill Cover Systems

Minimum technical requirements for closure of permitted HW landfills regulated under Subtitle C of RCRA are contained in 40 CFR §264.310. Analogous requirements for interim status HW landfills are contained in 40 CFR §265.310. These regulations allow a performance-based cover system design; no prescriptive design criteria are provided for HW landfills. The specific requirements of the regulations for permitted landfills are given below:

> "*(a) At final closure of the landfill or upon closure of any cell, the owner or operator must cover the landfill or cell with a final cover designed and constructed to:*
> *(1) Provide long-term minimization of migration of liquids through the closed landfill;*
> *(2) Function with minimum maintenance;*
> *(3) Promote drainage and minimize erosion or abrasion of the cover;*
> *(4) Accommodate settling and subsidence so that the cover's integrity is maintained; and*
> *(5) Have a permeability less than or equal to the permeability of any bottom liner system or natural subsoils present.*"

Cover system requirements for interim status HW landfills (40 CFR §265.310) differ in several details from those given above for permitted facilities. EPA (1991a) and Koerner and Daniel (1997) discussed these differences. EPA generally recommends, however, that cover systems for interim status HW landfills be designed to the same standards as permitted facilities.

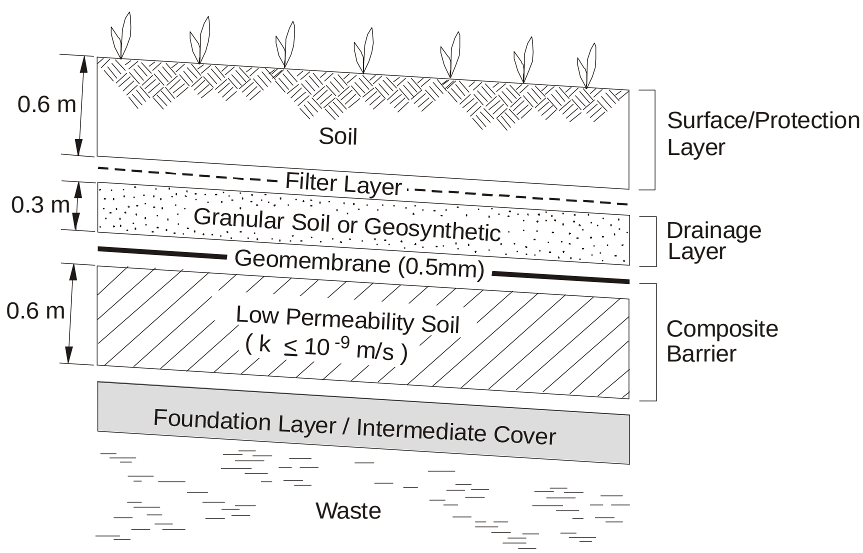


Figure 1-7. EPA (1989) Recommended Minimum Cover System for HW Landfills.

EPA previously issued minimum technology guidance for cover systems that meet the regulatory requirements of 40 CFR §264.310 (EPA, 1989). The cover system for HW landfills recommended in the 1989 EPA guidance consists of (Figure 1-7):

- a top layer containing two components: (i) either a vegetated or armored surface layer, selected to minimize erosion and, to the extent possible, promote drainage off the cover; and (ii) a protection layer, comprising topsoil and/or fill soil, as appropriate; the recommended top layer surface slope is 3 to 5%; the 1989 EPA guidance noted that the top layer soil component should be at least 0.6-m thick, and that a greater thickness may be required to assure that the underlying hydraulic barrier is below the frost zone;
- a soil drainage layer with minimum thickness of 0.3 m and a minimum hydraulic conductivity of 1 x 10^{-4} m/s that will effectively "*minimize water infiltration into the underlying low-permeability barrier*" and have a final slope of at least 3% after settlement and subsidence or a drainage layer consisting of a geosynthetic material with performance characteristics equivalent to the soil drainage layer; and
- a composite hydraulic barrier consisting of: (i) a GM with a minimum thickness of 0.5 mm; and (ii) a CCL with a minimum thickness of 0.6 m and a maximum hydraulic conductivity of 1 x 10^{-9} m/s; the EPA guidance notes that the entire hydraulic barrier should lie below the frost zone.

The 1989 EPA guidance indicated that optional layers may be used on a site-specific basis. According to the 1989 guidance, optional layers may include a gas collection layer placed below the hydraulic barrier, a biotic barrier component of the protection layer, and geosynthetic or soil filter layers. All of these types of materials are discussed in more detail in Section 1.5 and Chapter 2 of this document. The 1989 guidance also discussed the use of alternative designs. This subject too is discussed in Section 1.3 and Chapter 3 of this document. It is also reiterated that the 1989 document provides guidance on minimum design criteria. On a case-by-case basis, it may be necessary to provide additional components or capability to a HW landfill design. For example, it may be necessary to specify a drainage layer hydraulic conductivity greater than 1 x 10^{-4} m/s to assure no unacceptable build-up of hydraulic head in the cover system. As another example, the thickness of the protection layer may need to be greater than 0.6 m to adequately protect the hydraulic barrier component from freezing weather impacts in some northern climates.

1.2.3 Solid Waste Landfill Cover System Performance

Both the MSW and HW landfill regulations cited above specify as a performance criterion minimization of water percolation into the waste (or, equivalently, minimization of liquids migration through the landfill by preventing the bathtub effect). For a MSW landfill cover system designed to provide long-term minimization of water percolation, EPA recommends that the cover system be designed to allow no more than 0.1 to 1 mm/yr of percolation, with a specific value in that range selected based on the nature of the contained waste, the hydrogeological vulnerability of the site, and other factors. The Agency considers this performance criterion to apply as a maximum rate over a considered performance period (e.g., maximum rate over a 30-year post-closure simulation). A cover system containing a composite hydraulic barrier, properly constructed with rigorous construction quality assurance (CQA) to achieve intimate contact between the GM and CCL or GCL components of the composite barrier, can be designed to satisfy this criterion. Based on available analytical models for composite liner performance (e.g., Giroud and Bonaparte (1989)), EPA has concluded that a cover system with a maximum percolation rate in this range (i.e., 0.1 to 1 mm/yr) should prevent the "bathtub" effect conservatively assuming no absorption of moisture by the waste mass (i.e., steady-state water balance).

EPA recognizes that the above range of design percolation rates for MSW landfill cover systems is likely conservative with respect to preventing the "bathtub" effect since MSW generally has the capacity to absorb a substantial amount of water. Moreover, these rates may be lower than the accuracy of the numerical models and field methods that are currently used to assess cover system hydraulic performance. While EPA believes that a maximum percolation rate in the range of 0.1 to 1 mm/yr is generally an appropriate performance standard for MSW landfill cover systems, the Agency recognizes that different site-specific percolation rates may be acceptable for certain sites.

EPA is not yet recommending a design percolation rate for HW landfill cover systems. However, based on a comparison of the components of the prescriptive minimum criteria cover system for MSW landfills and the minimum technology guidance cover system for HW landfills, it can be inferred that the design percolation rate for HW landfill cover systems should be at the lower end of the range recommended by EPA for MSW landfill cover systems. It is also recognized that HWs can have a lower water absorption capacity than MSW wastes. Thus, HW landfill cover systems may require a higher level of performance to prevent the "bathtub" effect.

1.2.4 CERCLA Site Cover Systems

The remediation of CERCLA sites is governed under the National Contingency Plan (NCP) of 1985, as modified by the Superfund Amendments and Reauthorization Act (SARA) of 1986. Regulatory requirements for remediation of CERCLA sites are contained in 40 CFR §300. Remediation of these sites often involves installation of a cover system as part of a source control remedy for a landfill, waste pile or pit, or heavily contaminated area. EPA (1997a) reported that containment technologies, which typically include some form of cover system, have been used for approximately 40% of the source control remedies implemented through 1995 at CERCLA sites.

Design requirements for cover systems at CERCLA sites are generally based on the attainment of applicable or relevant and appropriate requirements (ARARs). ARARs for cover systems may include RCRA Subtitle C or Subtitle D regulations. EPA (1991a) provided a detailed discussion of ARARs development for CERCLA cover systems.

CERCLA MSW landfills represent a particular subset of CERCLA sites for which EPA has established presumptive remedy guidance (EPA, 1993). CERCLA MSW landfills typically contain a combination of principally MSW and, to a lesser extent, wastes containing hazardous substances. CERCLA MSW landfills represent approximately 20% of the total number of CERCLA sites in the United States (EPA, 1991b). The Agency has defined presumptive remedies as preferred technologies for common categories of sites, based on historical patterns of remedy selection for those categories of sites and EPA's scientific and engineering evaluation of performance data on technology implementation. For CERCLA MSW landfill sites, EPA has established containment as the presumptive remedy (EPA, 1993). Furthermore, the Agency has identified cover systems as a component of the source containment presumptive remedy. EPA (1993) provided the following guidance on establishing ARARs for CERCLA MSW landfill presumptive remedies:

> *"In the absence of Federal Subtitle D closure regulations, State Subtitle D closure requirements generally have governed CERCLA response actions at municipal landfills as applicable or relevant and appropriate requirements (ARARs). New Federal Subtitle D closure and post-closure care regulations will be in effect on October 9, 1993 (56 FR 50978 and 40 CFR §258). State closure requirements that are ARARs and that are more stringent than the Federal requirements must be attained or waived.*
>
> *The new Federal regulations contain requirements related to construction and maintenance of the final cover, and leachate collection, ground-water monitoring, and gas monitoring systems. The final cover regulations will be applicable requirements for landfills that received household waste after October 9, 1991. EPA expects that the final cover requirements will be applicable to few, if any, CERCLA municipal landfills, since the receipt of household wastes ceased at most CERCLA landfills before October 1991. Rather, the substantive requirements of the new Subtitle D regulations generally will be considered relevant and appropriate requirements for CERCLA response actions that occur after the effective date."*
>
> *"RCRA Subtitle C closure requirements may be applicable or relevant and appropriate in certain circumstances. RCRA Subtitle C is applicable if the landfill received waste that is a listed or characteristic waste under RCRA, and:*
> 1. *The waste was disposed of after November 19, 1980 (effective date of RCRA), or*
> 2. *The new response action constitutes disposal under RCRA (i.e., disposal back into the original landfill).*
>
> *The decision about whether a Subtitle C closure requirement is relevant and appropriate is based on a variety of factors, including the nature of the waste and its hazardous properties, the date on which it was disposed, and the nature of the requirement itself. For more information on RCRA Subtitle C closure requirements, see RCRA ARARs: Focus on Closure Requirements, Directive No. 9234.2-04FS, October 1989."*

The decision of whether MSW or HW landfill cover system requirements are relevant and appropriate also depends on the level of cover system hydraulic performance that must be achieved to provide human or ecological receptor exposure point concentrations that produce acceptable post-remediation human health and ecological risk estimates.

1.2.5 Liquids Management Strategy

EPA policies and regulations for landfill cover systems have evolved within a framework originally described by the Agency as a "liquids management strategy." The two main goals of the strategy are: (i) minimizing leachate generation by keeping liquids out of the landfill (or source area for a CERCLA remediation); and (ii) detecting, collecting, and removing leachate as it is generated (EPA, 1991c, 1992a). With this liquids management strategy, keeping water out of the landfill (or source area) becomes a prime performance objective for the cover system. In fact, EPA has stated (EPA, 1989):

> "*Thus, the Agency believes that a properly designed and constructed cover becomes, after closure, the most important feature of the landfill structure. The Agency requires that the cover be designed and constructed to provide long-term minimization of the movement of water from the surface into the closed unit. Where the waste mass lies entirely above the zone of ground-water saturation, a properly designed and maintained cover can prevent, for all practical purposes, the entry of water into the closed unit, and thus minimize the formation and migration of leachate.*"

Figure 1-8 illustrates the benefits of cover system installation in reducing leachate generation rates. This figure shows leachate generation rates for a GM-lined MSW landfill cell through the period of active cell operation, the closure period, and the first few years of the post-closure period. The landfill site is located in Pennsylvania and receives approximately 1,000 mm of precipitation annually, on average (Bonaparte, 1995). The landfill cover system includes a GM barrier. Monthly average leachate generation rates during the period of cell filling were up to 3,400 lphd. Rates for the first three years of the post-closure period were only 70 lphd. The very

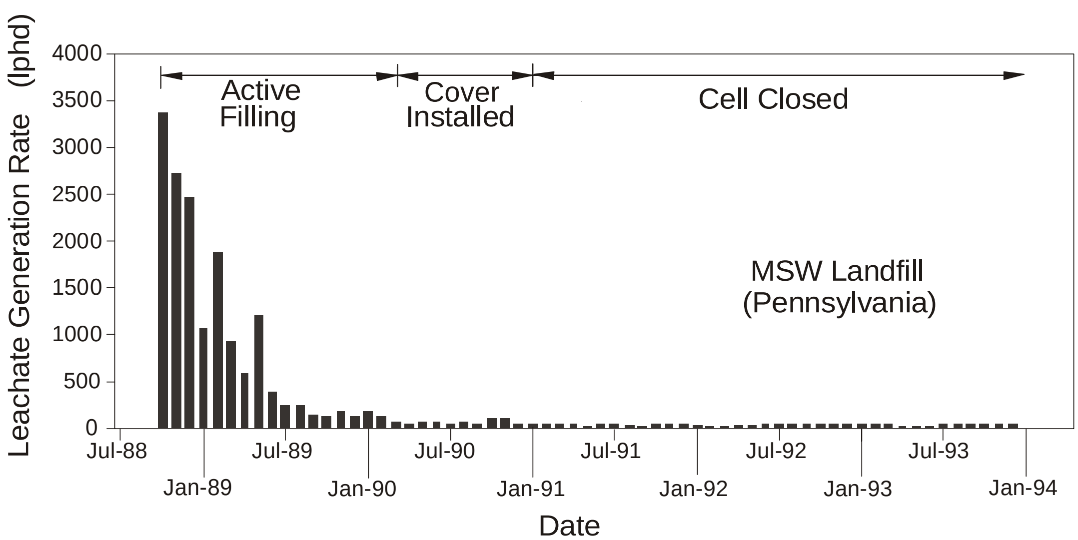


Figure 1-8. Leachate Generation Rates Over Time at a MSW Landfill in Pennsylvania (from Bonaparte, 1995). (Flow rates are in liters/hectare/day (lphd).)

significant effect of cover system installation on the rate of leachate generation is apparent. Figure 1-9 from Othman et al. (2002) shows similar behavior for a group of MSW and HW landfill cells that have a cover system that includes a GM. On average, leachate generation rates typically decreased by a factor of four within one year after closure and by one order of magnitude within two to four years after closure. Six years after closure, leachate generation rates were between 5 and 1,200 lphd (mean of 180 lphd). Nine years after closure, leachate generation rates were negligible. These data show that well designed and constructed cover systems can be effective in reducing leachate generation rates to very low or near zero values.

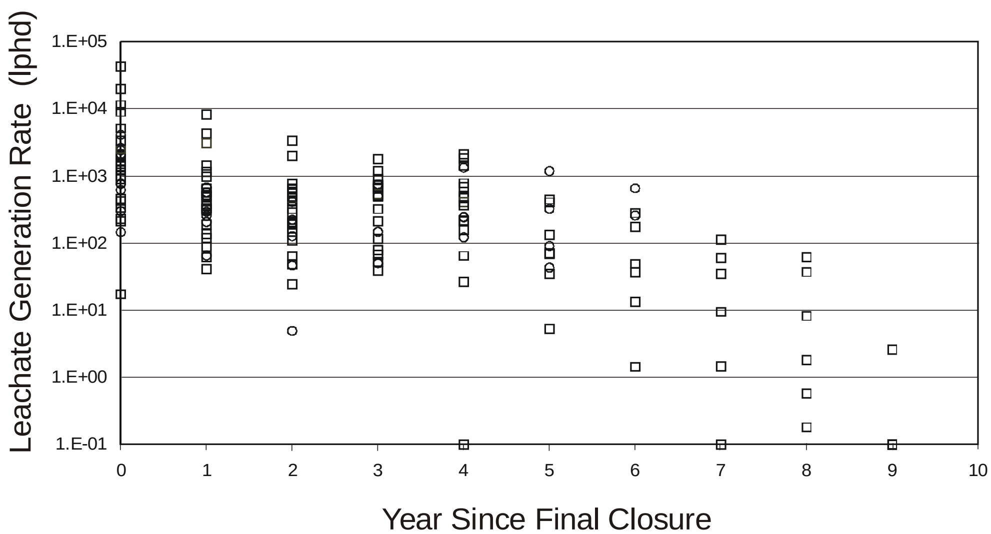


Figure 1-9. Effect of Cover system Installation on Leachate Generation Rates for 12 MSW Landfill Cells (shown as circles) and 22 HW Landfill Cells (shown as squares) (from Othman et al., 2002). (Note: flow rates of 0 lphd are shown as 0.1 lphd on this figure.)

1.2.6 Design Life

Consistent with the Agency's liquids management strategy, discussed above, the design life goal for RCRA and CERCLA cover systems is to minimize infiltration into the waste for as long as the enclosed waste poses an unacceptable risk to human health and the environment. A distinction must be made between the minimum post-closure care period of 30 years given in RCRA regulations and the design life of the cover system. The latter is much longer than 30 years and is defined primarily by the service life characteristics of the material used to construct the cover system. The service life of CCLs protected from freeze-thaw and other environmental effects, and not subjected to excessive differential settlements, should be indefinitely long (Mitchell and Jaber, 1990). The service life of any GM component of the cover system is dependent on the specific material used and how well the material is protected. The most extensive service life data currently available are for high density polyethylene (HDPE) GMs. The data indicate that the service life for commercially-available HDPE GMs will be measured in terms of at least several hundred years (Hsuan and Koerner, 1998; Hsuan and Koerner, 2002). Other types of GMs may have different service lives from that for HDPE GMs. Great care should be used in specifying GM materials to require products that, through polymer type, additive (e.g., antioxidant) packages, physical robustness, etc., are capable of achieving as long a service life as possible.

Achieving a design life measured in terms of hundreds of years requires more than just the selection of durable materials of construction. The design itself must be developed to achieve the design life criteria. This involves developing a design with adequate slope stability factors of safety, adequate flow capacity for the internal drainage system, adequate surface-water runoff controls, adequate freeze-thaw protection, adequate resistance to surface erosion, and appropriate vegetation or other surface treatment. Many of these design topics are addressed in subsequent chapters of this document. Recognizing the dynamic nature of the ecosystem in which cover systems must function, post-closure monitoring and maintenance are important elements in achieving the required design life. Long-term maintenance with respect to surface erosion, biointrusion, and plant succession (i.e., grasses to shrubs to trees) are particularly important issues in addressing the design life of a cover system. Monitoring of cover systems after closure is necessary to both satisfy regulatory requirements and assure the performance of the cover system. While performance monitoring is important for all closed facilities, it is particularly such for closed sites, such as old dumps and contamination source areas, and for sites with alternative cover systems. Monitoring of infiltration, soil moisture, gas emissions, and settlement is discussed in Chapter 8. The cover system must also be inspected and maintained to assure adequate performance of the site in the long term and to comply with regulatory requirements. Cover system maintenance is discussed in Chapter 9.

1.2.7 Other Regulatory Requirements

In addition to the regulatory requirements cited above, other regulatory requirements or ARARs may be applicable to a landfill closure or CERCLA remediation project. These additional requirements must be considered on a case-by-case basis. It is essential for proper design and legal compliance of the project that all potentially applicable regulations be identified during the design criteria development phase of the project (see Section 1.6 of this document). Other potential regulatory requirements or ARARs include:

- State-mandated cover system regulations that impose additional requirements beyond the minimum technical requirements of EPA;
- requirements imposed by other regulations for specific types of wastes, regulated under the Toxic Substances Control Act (40 CFR §700), such as polychlorinated biphenyls (PCBs), or Uranium Mill Tailings Remediation Act (40 CFR §192);
- State or Federal (including Federal Emergency Management Agency) requirements for site surface-water management, landfill gas management, seismic design, or other requirements that could influence the design of the cover system;

- provisions for management, treatment, and/or discharge of stormwater runoff, leachate, gas condensate, or other liquids under provisions of the Clean Water Act, including National Pollution Discharge Elimination System (NPDES) requirements (40 CFR §122) and proposed landfill point source effluent limitation guidelines (40 CFR §445);
- State or local (including National Resources Conservation Service) requirements for maximum allowable soil erosion rates, erosion control structure design and performance, and surface-water management structure design and performance;
- Federal, State, or local requirements for siting, including limitations on construction in floodplains, disturbance of wetlands, and construction on or near Holocene faults; and
- local building and development codes if re-use of the site is expected.

1.3 Alternative Design Concepts and Materials

RCRA and CERCLA regulatory requirements provide flexibility for innovation and alternatives by limiting the use of specific minimum design specifications as much as possible, by providing performance criteria in lieu of design specifications, and/or by providing administrative procedures for gaining approval of waivers from RCRA regulatory requirements or CERCLA ARARs.

EPA is open to considering alternative designs on a case-by-case basis. Determinations on the acceptability of alternative designs are the responsibility of the Regional Administrator. Statutory requirements must be satisfied by any approved alternative. This document provides guidance on several of the alternative design approaches and materials that the Agency will consider on a case-by-case basis. It is anticipated that new design approaches and materials will be considered by EPA in the future as the performance of these alternatives is demonstrated and proven. As an example of an alternative design, Region 1 of EPA has issued alternative minimum technology guidance for closure of unlined HW landfill sites in that region. The rationale and technical analyses supporting the Region 1 alternative minimum technology guidance is given in EPA (1997b). It is noted that, in Region 1, this type of landfill often has relatively steep sideslopes (i.e., greater than 6 horizontal:1 vertical (6H:1V)) and soils suitable to construct a hydraulic barrier may not be locally available. A comparison of the minimum technology guidance from EPA (1989) and EPA (1997b) is presented in Figure 1-10. Other types of alternative designs may involve ET or capillary barriers as discussed in Section 1.1 of this document. Alternative design concepts and materials are discussed in more detail in Chapter 3.

The minimum technical requirements for cover systems were developed by EPA to achieve the liquids management strategy goal previously described. These requirements still represent the Agency's preferred approach for most types of landfills under most situations. In recent years, however, the Agency has begun to consider other management strategies for landfill facilities. Potential strategies include, for example, landfill leachate recirculation and bioreactors (EPA, 1995). EPA believes that new landfill management strategies may lead to new alternative cover system designs and materials. The Agency is currently considering these types of alternatives on a case-by-case basis.

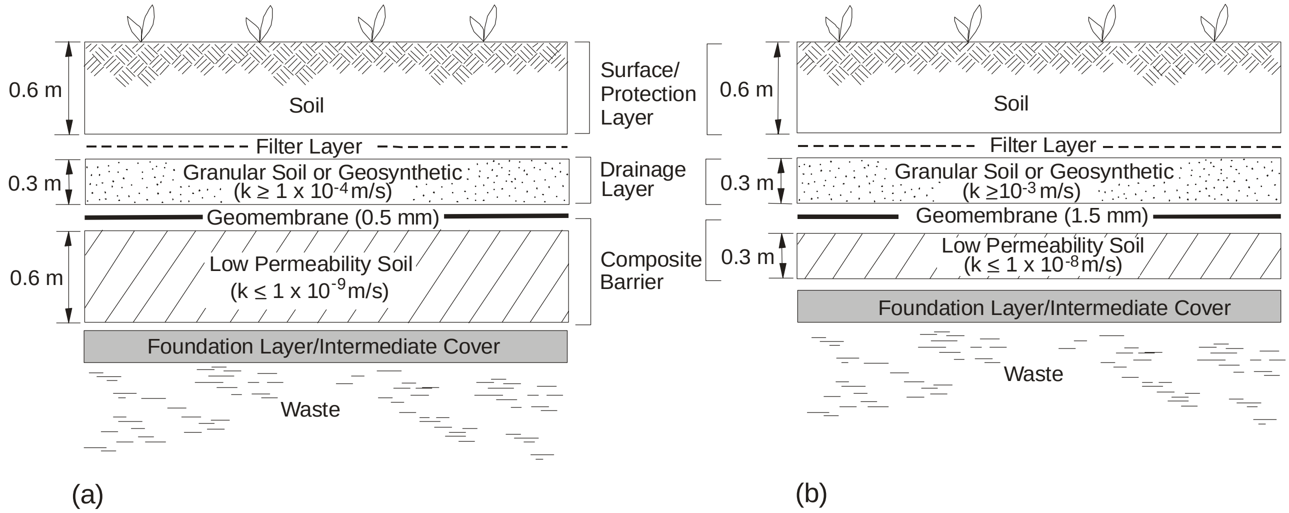


Figure 1-10. Comparison of Cover Systems for HW Landfills: (a) EPA (1989) Recommended Minimum Technology Cover System; and (b) Region 1 Alternative Minimum Cover System.

The use of monitored natural attenuation is recognized by EPA as a viable technique for remediation of soil and groundwater at certain sites (EPA, 1999a). The term "monitored natural attenuation" refers to the reliance on natural attenuation processes to achieve site-specific remedial objectives within a time frame that is reasonable, compared to that offered by other more active remediation methods. The "natural attenuation processes" that are at work in such a remediation approach include a variety of physical, chemical, and/or biological processes that, under favorable conditions, act without human intervention to reduce the mass, toxicity, mobility, volume, or concentration of contaminants in soil or groundwater. These in-situ processes include biodegradation, dispersion, dilution, sorption, volatilization, radioactive decay, and chemical or biological stabilization, transformation, or destruction. EPA is aware of situations where monitored natural attenuation has been proposed along with a permeable (e.g., granular) cover system as a source control remedy for a CERCLA landfill. Since this approach is not consistent with the Agency's liquids management strategy, EPA will evaluate these cover systems very carefully on a case-by-case basis and, in some cases, will require that an in-situ treatment technology be used with this approach to complement natural attenuation and a demonstration of the technical practicability of the technology. As an example, this remediation approach is being used by EPA Region 1 for the Somersworth Sanitary Landfill Superfund Site. As outlined in the 1995 Consent Decree for the site, the Preferred Source Control Remedy includes:

- "*placement of a permeable cover over the landfill allowing precipitation to flush contamination from the waste management area. This cover will remain as long as contaminants continue to leach from the waste within the waste management area and the chemical treatment "wall" is functioning. After the Final Cleanup Levels have been achieved and can be maintained with use of the treatment "wall," an appropriate landfill cover to close the landfill that is consistent with the ROD* (Record of Decision) *shall be installed and maintained.*";

- "*installation of a treatment wall composed of impermeable barrier sections and permeable, chemical treatment sections to provide in-situ (in-place), flow-through treatment of contaminated ground water at the down-gradient edge of the waste management area.*" (the site and the pilot-scale treatment wall is described in EPA (1999b)); and
- "*enhancements … and additional source control measures, if necessary*".

The Consent Decree for this site places the burden of using the alternative source control remedy on the party implementing the remedy. If the Preferred Source Control Remedy does not meet the specified performance standards, a Contingent Source Control Remedy, including installation of a cover system that meets RCRA Subtitle C requirements and other ARARs, may need to be implemented.

1.4 Gas Management Requirements

Landfill gas collection and control is necessary at some MSW landfills, a limited number of HW landfills, and some CERCLA remediation sites. Most modern MSW landfills built to current regulatory standards have landfill gas collection and control systems. Some sites recover the gas for its energy potential, which may help to offset regulatory compliance costs. As of January 1999, there were about 300 MSW landfill gas-to-energy projects active in the U.S and several hundred more planned or in construction (Thorneloe, 2000).

Anaerobic decomposition of organic material in waste is the principal source of landfill gas and a significant cause of settlement of the waste mass. Some industrial wastes, however, can generate gas by inorganic chemical reactions. Gas production rates vary with the composition and age of waste, waste volume, waste moisture content, and other factors. MSW landfill gas consists mainly of methane and carbon dioxide, with lesser concentrations of nitrogen, oxygen, sulfides, ammonia, and other constituents, and trace concentrations of a variety of volatile organic compounds, including vinyl chloride, ethylbenzene, toluene, and benzene (Tchobanoglous, 1993). Landfill gas can be a significant threat to human health and the environment (EPA, 2000). Because of this, CAA regulations establish requirements for MSW landfill gas collection and control at certain facilities. Gas generation in a MSW landfill cell can extend over a period of 25 years or more, or gas generation can be accelerated through the use of leachate recirculation. An idealization of gas generation rates in MSW landfills is presented in Figure 1-11.

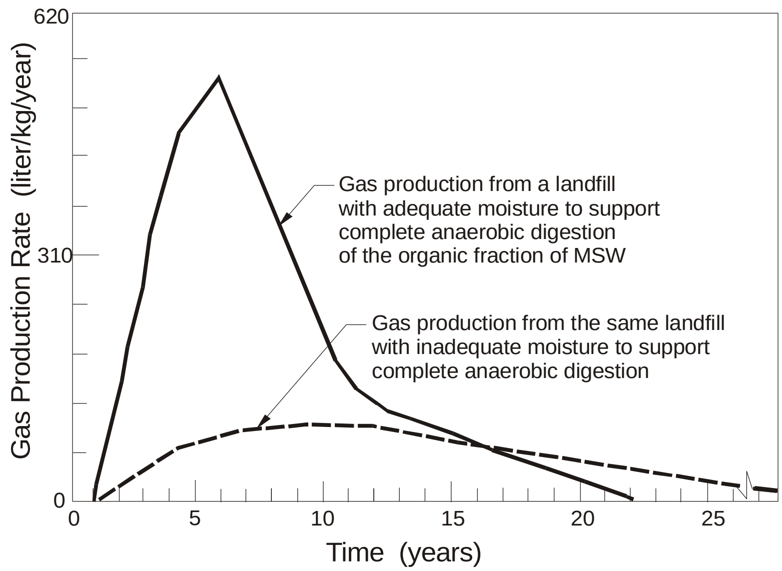


Figure 1-11. Idealization of Gas Generation Rates in MSW Landfills (from Tchobanoglous, 1993).

Gas emissions from MSW landfills are presently governed by two sets of regulations that may influence the design of landfill gas collection and control systems associated with the cover systems. A third regulation was proposed in November 2000 (EPA, 2000). RCRA Subtitle D regulations address the personal and fire/explosion safety aspects of landfill gas under 40 CFR §258.23, which requires:

> "*(a) Owners or operators of all MSWLF units must ensure that:*
> *(1) The concentration of methane gas generated by the facility does not exceed 25 percent of the lower explosive limit for methane in facility structures (excluding gas control or recovery system components); and*
> *(2) The concentration of methane gas does not exceed the lower explosive limit for methane at the facility property boundary*."

The second set of regulations governing MSW landfill gas is the New Source Performance Standards (NSPS) and Emissions Guidelines (EG) promulgated under the Clean Air Act (CAA). The NSPS and EG regulate emissions of non-methane organic compounds (NMOCs) as a surrogate to total landfill gas emissions (40 CFR §60.755). MSW landfills with design capacities equal to or greater than 2.5 million megagrams and 2.5 million cubic meters with NMOC emission estimates of 50 megagrams or more per year must have: (i) a well designed and operated gas collection system; and (ii) a control system device capable of reducing NMOC mass in the collected gas by 98%.

The third regulation proposes national emission standards for hazardous air pollutants (NESHAP) for MSW landfills identified as major sources of hazardous air pollutants (HAP) listed in Section 112(b) of the CAA and some MSW landfills identified as area sources (EPA, 2000). The proposed NESHAP contains the same requirements as the EG and NSPS as well as some additional requirements to further reduce HAP emissions to the level reflecting the maximum achievable control technology (MACT). The total impact on MSW landfills is expected to be limited.

Additional information on gas management regulations for MSW landfills can be found at http://www.epa.gov/ttn/atw/landfill/landflpg.html. EPA is currently developing a document that provides information on methodologies for assessing landfill gas emissions and health risks at CERCLA landfills. The document is also of help to non-CERCLA sites where CAA regulations are not applicable. The document and accompanying fact sheet are to be released in 2004 and will provide information on the requirements of the CAA regulations for CERCLA landfills and information on assessing the landfill gas emissions and controls.

Waste-generated gas affects cover systems in several ways. The presence or absence of gas influences the selection of the type of hydraulic barrier material. GMs are generally better barriers to gas migration than soils, with the possible exception of intact CCLs at or near saturation (although low-permeability soils at saturation can have low shear strength and drying of the soil is a concern). Also, it may be necessary to install a gas collection layer beneath the barrier to convey gas to outlets through the cover system, or alternatively to install gas extraction wells or trenches at a sufficiently close spacing to prevent gas build-up beneath the barrier.

A factor sometimes overlooked in the closure of old landfills and in remediation of contamination source areas is that placement of a cover system will trap any gas being generated by the waste. Gas generation rates at these facilities may be slow enough that gas generation is not even recognized as a design issue. Yet after cover system installation, gas pressure can slowly build up. This process may eventually lead to one or more of the following: (i) problems with cover system performance, including a reduction in the factor of safety along interfaces in the cover system below the hydraulic barrier; and (ii) for unlined or inadequately lined landfills and contamination source areas, subsurface gas migration. Subsurface gas migration has caused adverse groundwater quality impacts at many older, unlined landfills and may also cause increases in atmospheric emissions of gas and safety or health impacts to nearby residences both from gas migrating through the soil and being released from groundwater passing beneath a residence. EPA recommends that the potential for landfill gas generation and impacts to nearby residences or businesses always be carefully evaluated as part of any landfill closure or remediation project.

Another factor to be noted is the trend towards recirculation of leachate and addition of other liquids to promote decomposition of landfilled waste. This results in faster and greater gas production than conventional landfills. These factors need to be considered in the final cover design to ensure adequate protection to near-by residents and the environment.

1.5 Typical Cover System Components

Components of a typical hydraulic barrier cover system are briefly introduced here and discussed in more detail in Chapter 2. The usual sequencing of these components is illustrated in Figure 1-12.

1.5.1 Surface Layer

The topmost component of a cover system is the surface layer. The primary functions of this layer are to resist erosion by water and wind, be maintainable, and provide a growing medium for vegetation, if present. The surface layer may also serve other purposes, such as promoting ET or satisfying project aesthetic, ecological, or end use criteria.

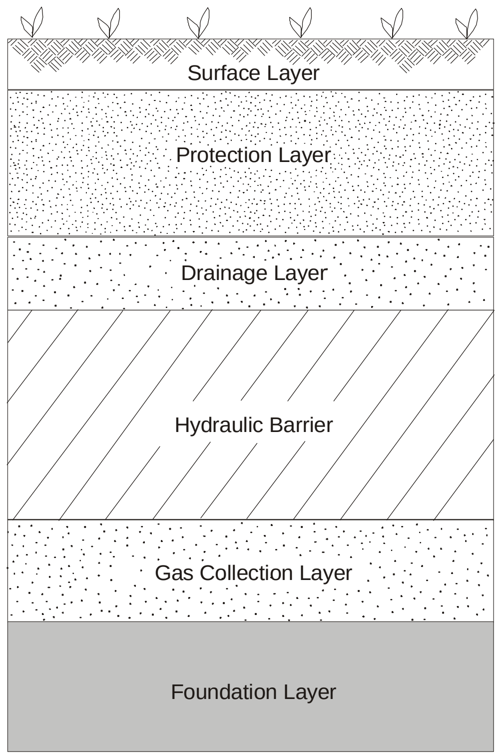


Figure 1-12. Typical Hydraulic Barrier Cover System Components.

Materials that can be used for cover system surface layers include: (i) topsoil; (ii) amended topsoil; (iii) gravel-soil mixtures; (iv) gravel; (v) riprap; (vi) articulated block systems; (vii) asphaltic concrete; and (viii) other materials. Of these materials, topsoil is, by far, the one most commonly used. Suitable topsoil promotes growth of vegetation, thereby maximizing the ET component of the cover system water balance. Vegetation also decreases the quantity and velocity of stormwater runoff on the cover system slopes and reinforces the topsoil; both of these effects reduce the rate of topsoil erosion in comparison to a topsoil layer without vegetation. At sites with conditions unfavorable to maintaining an adequate growth of vegetation (e.g., sites with steep slopes or in semi-arid or arid climates), gravel-soil mixtures, gravel, riprap, articulated block systems, or other materials may be used for the surface layer.

1.5.2 Protection Layer

A protection layer may serve several functions:

- protect underlying layers from erosion;
- protect underlying layers from exposure to wet-dry cycles, which may cause degradation of these layers;
- protect underlying layers from exposure to freeze-thaw cycles, which may cause degradation of these layers;
- serve as a barrier to human, burrowing animal, or plant root intrusion (i.e. a biobarrier);
- temporarily store water that has infiltrated through the surface layer until the water returns to the atmosphere through ET; this action provides a water reservoir to support plant growth and reduces infiltration into underlying cover system layers; and
- restrict emissions of radon gas for those wastes, such as uranium mill tailings, that emit radon.

On-site or locally available soil is usually suitable for protection layer construction if the primary functions of the layer are to support vegetation and protect underlying layers from cracking due to wet-dry and freeze-thaw effects. However, if the primary role of the protection layer is to prevent biointrusion, cobbles, asphaltic concrete, or similar materials are typically required.

1.5.3 Drainage Layer

In a hydraulic-barrier type cover system, a drainage layer may be required beneath the protection layer and above the hydraulic barrier, particularly on sideslopes. A drainage layer may serve several functions:

- limit the buildup of hydraulic head on the underlying hydraulic barrier, which minimizes percolation of water through the barrier;
- drain the overlying surface and protection layers, which increases the available water-storage capacity and helps to minimize erosion by reducing the time during which the layers remain saturated with water; and
- reduce the seepage forces in the protection, surface, and drainage layers, which improves cover system slope stability.

Materials used for drainage layers include sand, gravel, geotextile (GT), geonet (GN), and geocomposite (GC) drainage materials. The material used must have adequate hydraulic conductivity to minimize the buildup of hydraulic head above the hydraulic barrier and adequate hydraulic transmissivity to convey the design flow rate. If gravel or a GN is used for the drainage layer, a filter layer will usually be needed between the drainage layer and the overlying protection layer to prevent fines from clogging the drainage layer. GT filter layers are typically used to achieve this function, although soil filter layers can also be used. If the drainage layer consists of gravel, and the underlying barrier is a GM, a GT cushion layer is typically needed between the GM and gravel. One of the most important aspects of designing a drainage layer is providing for free drainage at the drainage layer outlet.

1.5.4 Hydraulic Barrier

The function of the hydraulic barrier is to minimize percolation of water through the cover system by impeding infiltration into the barrier and by promoting storage or lateral drainage of water in the overlying layers. Properly designed, constructed, and maintained hydraulic barriers can virtually eliminate infiltration into the waste. Hydraulic barriers also restrict migration of gas or volatile constituents from the waste mass to the atmosphere.

Materials used for hydraulic barrier construction include GMs, GCLs, and CCLs. Each of these barrier materials may be used alone or in combination. It has been shown, however, that, all else being equal, a cover system with a composite barrier consisting of GM/CCL, GM/GCL, or GM/GCL/CCL allows less percolation than a cover system with a GM, GCL, or CCL barrier.

1.5.5 Gas Collection Layer

Gas collection layers may be necessary beneath cover system barriers for wastes that generate gas or emit volatile constituents. These layers are designed to have adequate in-plane gas transmissivity to convey gas to passive gas vents, active gas wells, or trenches. Gas collection layers are typically a necessary complement to systems that utilize passive gas vents. Gas collection layers may not always be needed for landfills with active gas extraction systems, depending on gas generation rates in the landfill, extraction well spacing, presence or absence of horizontal gas trenches, and other factors.

Gas collection layers may be constructed of granular materials (e.g., sand or gravel) or geosynthetics (e.g., GT, GN, GC). The selected material must have adequate transmissivity to minimize the build up of gas pressures beneath the barrier and convey the design gas flow rate. When a granular material is used, a separation layer (typically a GT) may be needed to separate the granular material from the overlying barrier.

1.5.6 Foundation Layer

The foundation layer is the bottom-most component of the cover system. The functions of the foundation layer are to provide grade control for cover system construction, adequate bearing capacity for overlying layers, a firm subgrade for compaction of overlying layers, a smooth surface for installation of overlying geosynthetics, and, in some applications, a buffer zone to reduce the potential effects of waste differential settlements on the cover system components.

Materials most often used for the foundation layer include on-site or locally available soils. Sometimes, intermediate cover soil already in place is used for all or a portion of the foundation layer. In a few situations, waste material can be used to construct the foundation layer. If constructed of granular material, the foundation layer may also serve as a gas collection layer.

1.6 Design Criteria Development and Conceptual Design

1.6.1 Overview

Gross et al. (2002) present the results of a survey conducted for EPA on problems and lessons learned at representative landfill facilities located throughout the U.S. The survey identified 69 modern landfill facilities that had experienced 80 liner system or cover system problems. For the study, a "modern facility" was considered one with components substantially meeting current EPA regulations and constructed and operated to the U.S. state-of-practice from the mid-1980's forward. Almost 30% of the problems identified in the study involved landfill cover systems. The percentage of cover system problems for the 69 facilities will likely be higher in the future since a number of these facilities were active and did not yet have a cover system. The primary factor contributing to the cover system problem in most cases was inadequate design.

The number of facilities in the EPA study is small compared to the total number of modern landfills nationwide. However, the search for problem facilities was not exhaustive. The Agency believes many more facilities than identified in the study have experienced the types of problems identified in the study. As pointed out in the EPA study, the single factor that can most improve the performance record for waste containment systems is improved design practice by the engineering community. It is imperative and consistent with the standard of professional care that engineers prepare complete, detailed, and proper designs of cover systems. Simple and incomplete design approaches intended to simply satisfy regulatory requirements and "get the grass growing" are not acceptable. This guidance document is intended to contribute to improved practices with respect to the design of cover systems.

The critical first steps in designing a landfill cover system involve: (i) developing the criteria that will be used to guide the design; (ii) preparing a conceptual design using these criteria; (iii) identifying data gaps based on the conceptual design; and (iv) performing predesign studies to generate the data needed to prepare the detailed design and construction plans and specifications. Design criteria development is addressed in more detail below.

1.6.2 Regulatory Requirements

The first step in establishing design criteria is to identify all applicable regulatory requirements (for a RCRA Subtitle D or Subtitle C facility) or ARARs (for a CERCLA site remediation). General guidance on applicable regulatory requirements was given in Section 1.2 of this document. Federal regulations are found in the Code of Federal Regulations and are available on the U.S. Government Printing Office website at http://www.access.gpo.gov/nara/cfr/cfr-table-search.html. State and local regulations may also be available on-line.

1.6.3 Climatic Criteria

Climate significantly affects cover system design and performance. For example, the typical approach to preventing water percolation through a cover system for a facility in the eastern U.S. is to use a low-permeability hydraulic barrier. In arid regions of the western U.S., however, the same design objective can be achieved using an ET barrier. As another example, climatic factors influence the thickness of the cover soil required to protect an underlying hydraulic barrier from the effects of freeze-thaw. Further, climatic factors greatly affect the types of vegetation that can be grown on a cover system.

Climatic criteria to consider in the design of a cover system include the amount and seasonal distribution of precipitation, duration of specific storm events (e.g., 1-hour storm event, 24-hour storm event, etc.), intensity of specific storm events (e.g., 25-year recurrence interval storm event, 100-year recurrence interval storm event, probable maximum precipitation (PMP), etc.), seasonal temperature variations and extremes, depth of frost penetration, quantity of snow melt, wind speed and direction, solar radiation and humidity. In some areas (e.g., cold, arid), the controlling climatic criterion for percolation may be snowmelt.

1.6.4 Physical and Engineering Criteria

Physical criteria that should be considered in designing a cover system include the lateral limits of waste, property setback requirements, if any, height of facility above surrounding ground, sideslope length and inclination, top deck length and inclination, depth of waste within the facility, type and thickness of interim cover, and potential for the waste to generate gas. A distinction must be made at this stage between proposed landfills where the design engineer has control over essentially every physical parameter for the facility versus an existing landfill or CERCLA remediation site where the design engineer must start the design process by considering the pre-existing site conditions. The consequences of a certain design action can be quite different for these two situations. For example, it is a relatively straightforward matter to design and construct a stormwater management or slope stability terrace or bench for a new landfill. Conversely, design and installation of a terrace or bench for a cover system on a steep pre-existing landfill slope can be difficult or infeasible. The latter type of design requires either that a cut be made into the existing waste slope or, alternatively, that the terrace be built up above the waste slope using soil fill and foundation/slope reinforcement techniques. These kinds of differences should be considered by the design engineer during design criteria development.

Design criteria development for a cover system should also consider a number of engineering criteria. The design engineer must carefully consider which engineering criteria are relevant for a particular facility, and then apply them appropriately. For each engineering criterion that must be satisfied, the design engineer must define: (i) performance requirements for that criterion; (ii) method of analysis or evaluation; and (iii) required input parameters with numerical values for each parameter and at least qualitative, if not quantitative, consideration of the uncertainity (i.e., standard deviation, standard error, etc.) associated with the selected numerical values. As an example, a common engineering criterion for landfill cover systems is long-term static stability of the waste mass beneath the cover. The performance requirement for this criterion is usually expressed in terms of a factor of safety against slope instability. The minimum acceptable factor of safety might be 1.5, for example. (A discussion of recommended slope stability factors of safety is given in Chapter 6 of this document.) A method of analysis that could be used to evaluate this criterion is a two- or three-dimensional limit equilibrium method of slices. Input parameters for the evaluation include the geometry of the waste, unit weight and shear strength of the waste, existence of any perched or continuous zones of leachate in the waste, existence of landfill gas pressures beneath the cover system, and the thicknesses, unit weights, internal shear strengths, and interface shear strengths of the cover system installed over the waste.

A partial list of engineering criteria that must frequently be considered in the design of RCRA or CERCLA cover systems with the components shown in Figure 1-12 are listed in Table 1-1 below. Not all criteria apply to all cover systems.

Table 1-1. Common engineering criteria for RCRA and CERCLA cover systems.

Slope Stability • Foundation stability • Waste mass stability • Cover system veneer stability • Pseudo-static stability analysis • Other stability conditions	**Settlement (Total and Differential)** • Foundation total settlement • Waste mass total settlement • Foundation differential settlement • Waste mass differential settlement
Seismic Deformation Analysis • Foundation liquefaction • Waste mass deformation • Cover system deformation	**Surface-Water Runoff Control** • Estimated peak flow rate • Surface-water control structure design (benches, channels, and retention ponds)
Geosynthetic Component Performance • GT filter layer requirements • GT clogging potential • GN/GC flow rate • GN/GC clogging potential • GN/GC compression resistance • GN/GC outlet design • GT cushion layer requirements • GM design (type, thickness, elongation and strength requirements) • GCL design (type, internal reinforcement, overlap)	**Erosion Control and Vegetation** • Rill and interrill erosion • Gully formation (tractive force analysis, critical distance for gully formation, permissible velocity analysis) • Wind erosion • Vegetation requirements (type, planting, fertilizer, amendments) • Temporary and permanent erosion control material requirements
Soil Component Performance • Erosion resistance of surface layer • Biointrusion resistance • Water storage capacity • Frost penetration depth • Drainage layer flow rate • Drainage layer clogging potential • Drainage layer outlet design • Granular filter layer requirements • Soil barrier hydraulic design (suitable soil availablity, thickness, hydraulic conductivity)	**Hydraulic Performance** • Cover system water balance • Percolation through cover system • Water flow in drainage layer • Maximum head in drainage layer **Gas Emission Control** • Gas emission rate analysis • Gas flow and pressure in collection layer • Gas collection system (active or passive) • Gas treatment requirements

The foregoing list of criteria, while extensive, is by no means exhaustive. Additional criteria will need to be considered on a case-by-case basis. Also, particular attention must be given to applicable engineering criteria any time an alternative or innovative cover system is proposed, as past precedent for such systems will, by definition, be limited or nonexistent.

1.6.5 Aesthetic and Land Use Criteria

Aesthetic and land use criteria are becoming more important in the design of cover systems. More and more, facility owners, regulators, and the local community are sensitive to the aesthetics of closed waste management sites. Today, it is not uncommon to design aesthetic enhancements into site closure projects. When such enhancements are to be used, they must be adequately designed in their own right, and any impact they may have on any other engineering criterion identified previously in this section must be addressed. Examples of aesthetic enhancements that have been incorporated into cover systems include:

- construction of an undulating sideslope to provide a more natural looking landform (compared to long, planar sideslope);
- planting of trees and shrubbery on terraces; and
- construction of decorative block retaining walls.

Increasingly, beneficial post-closure land uses are being considered in the design of cover systems for landfill closures and CERCLA remediations. The most common types of end uses are parks, hiking trails, sports fields, and golf courses. The selected end use can have a significant impact on cover system design. For example, if a site is to be used for a golf course or other facility with a vegetated surface layer that requires irrigation, the cover system may require an internal drainage layer and a barrier that includes a GM to control percolation through the cover system (Hauser, 2000). Figure 1-13 shows a completed CERCLA remediation in southern California where the site was closed with a multi-component soil and geosynthetic cover system, and a golf course was developed on the cover system. Further discussion of aesthetic enhancements and post-closure land uses for cover systems is given in Chapter 9 of this document.

1.6.6 Ecological Criteria

Conventional engineering approaches for designing cover systems often fail to fully consider ecological processes at work in the local environment. Natural ecosystems effective at capturing and/or redistributing materials in the environment have evolved over millions of years. Consequently, when contaminants are introduced into the environment, ecosystem processes begin to influence the distribution and transport of these materials, just as they influence the distribution and transport of nutrients that occur naturally in ecosystems (Hakonson et al, 1992). As the ecological status of a cover system changes, so will performance factors such as water infiltration, water retention, ET, soil erosion, and biointrusion. An objective often overlooked in designing cover systems is to cause subsequent ecological change to enhance and preserve the encapsulating system. Only through a holistic ecological approach can long-term maintenance requirements for cover systems be truly minimized (Caldwell and Reith, 1993). Consideration of natural analogs can enhance the design of a cover system by disclosing those processes that are active in a given environment or the mechanisms that could lead to failure. These mechanisms can then be avoided through appropriate design and construction. Natural analog studies provide clues from past environments that can be applied to the long-term behavior and performance of a cover system. Analog studies involve the use of logical analogy to investigate natural and archaeological occurrences of materials, conditions, or processes that are similar to those known or predicted to occur in some part of the cover system (Waugh, 1994). Perhaps the simplest examples of a natural analog for a cover system are the stable soil geomorphology in the locality of a project. Local soil geomorphology may be an indicator of the erosional stability of local soils used for the surface/protection layer in a cover system. For example, if a local glacial till is to be used for the surface/protection layer of a landfill, and all the local landforms containing that fill have evolved with slopes no steeper than a certain value, then use of that till on steeper cover system slopes contravenes the local geomorphological evidence, suggesting a greater likelihood of long-term maintenance requirements than might otherwise be the case.

A primary goal of design is to achieve a cover system that is as maintenance-free as possible. While it is debatable as to whether the need for all long-term maintenance can be eliminated, significant progress is possible with respect to current engineering practice. Moreover, in virtually all cases, some degree of maintenance or post-construction refinement may be necessary until the cover system reaches a state of equilibrium with its inherent environment.

Figure 1-13. Example of Post-Closure Land Use: Closed California CERCLA Site Used as a Golf Course.

An important point often not recognized is that a cover system should be stabilized with vegetation comprising plant communities that closely emulate a selected local “climax” community (Caldwell and Reith, 1993). A climax community, in ecological terms, is defined by the environmental parameters of the community (e.g., climate, soil, and landscape properties, fauna, and other flora). Central to the concept of “climax” is the community’s relative stability in the existing environment (Whittaker, 1975). A diverse mixture of native plants on a cover system maximizes water removal through ET (Link et al., 1994). The cover system is then more resilient to natural and man-induced catastrophes and fluctuations in environments. Similarly, biological diversity in cover system vegetation is important to community stability and resilience given variable and unpredictable changes in the environment resulting from pest outbreaks, disturbances (overgrazing, fires, etc.), and climatic fluctuations. Local native species that have been selected over thousands of years are best adapted to disturbances and climatic changes (Waugh, 1994). In contrast, planting of non-native species, as is common in the current standard-of-practice for landfill and containment system engineering, is genetically and structurally monotonous (Harper, 1987) and therefore more vulnerable to disturbances. Pedogenic processes gradually change the physical and hydraulic properties of earthen material cover systems (Hillel, 1998). Plant communities inhabiting the cover system will also change in response to these changes in soil properties.

A cover system that is to last for hundreds of years, or longer, must be designed as an integral component of a larger dynamic ecosystem. Cover system components initially designed for a specific purpose such as a barrier or drainage layer will not function independent of one another. Therefore, these systems should be considered not only individually, but also as a system (linked assemblage of components). Inevitable changes in physical and biological conditions should be taken into account to help ensure the long-term effectiveness of the cover system.